ANALYSIS OF A LEAKY ARTESIAN AQUIFER IN NORTHWESTERN OHIO

Senior Thesis

by

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CONTENTS

ILLUSTRATIONS

ABSTRACT

Controlled pumping tests of aquifers provide a means of obtaining data for evaluation of hydraulic properties. With these data, it is possible to make some predictions concerning availability of water under sustained pumping conditions. The following is an aquifer analysis based on data collected by The Ohio Division of Water on July 28-31, 1969.

Figure 1. Map Showing general location of test wells.

INTRODUCTION

The NWO (Northwest Ohio Project), which is being conducted by the Ohio Division of Water, is designed to provide a general evaluation of aquifers in the northwest part of the State. Ultimately, the entire State will be catalogued relative to availability of ground water. The purpose behind NWO is to provide answers to questions such as: how much water is available?, what depth is the most productive?, what is its chemical quality?, and, roughly, what will be the response of the aquifer to sustained pumping?

An aquifer is defined as a bed or series of beds of rock that will supply a sufficient amount of water to a well. Sufficient for what? A city well field, a canning plant, or perhaps a single house well. The NWO project is designed to provide some meaning to the term "sufficient." Therefore, a quantitative appraisal of aquifers in Ohio is the main purpose of the project. In addition, much can be learned about the subsurface geology of the State, since a careful record is kept of well cuttings, chemical analyses of the water from the wells are made in the field, and a sample of the water collected for a detailed laboratory analysis.

The occurrence and movement of ground water have been poorly understood since people have been aware of its presence. The "mysteries" surrounding the occurrence of ground water are understandable, since the water is invisible while it is still in the ground.

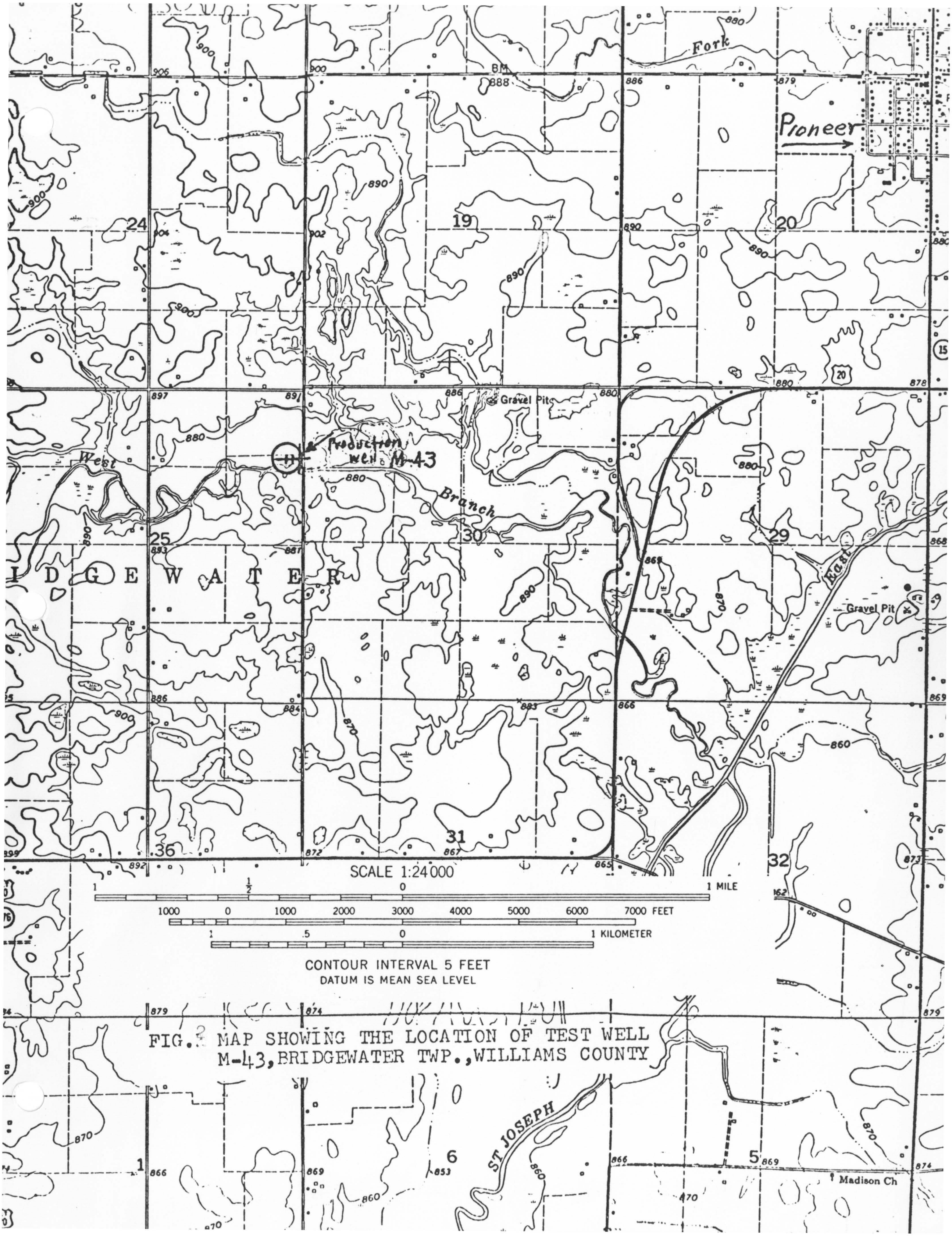


FIG. 2 MAP SHOWING THE LOCATION OF TEST WELL
M-43, BRIDGEWATER TWP., WILLIAMS COUNTY

In the past 50 years, however, there has been considerable progress in our knowledge of the occurrence and movement of ground water as well as aquifer evaluation. Improved well construction techniques have provided part of the impetus for this advance. Further incentive to study ground water hydraulics has come from increased development of ground water reservoirs as surface reservoirs become polluted, overdeveloped, or insufficient for the municipal and industrial needs. As ground-water development intensifies, well owners and water management agencies will become more interested in the response of aquifers to heavy pumping. Competition for available water resources has made people realize that one of the problems facing the hydrologist is resource management. Before water resources can be managed, they must first be quantitatively appraised. In ever increasing numbers, engineers and hydrologists are being asked to estimate how much ground water is available for development, and what will be the consequences of exploitation. Ground water users are continually asking for suggestions as to how available resources can be properly managed.

Ground water reservoirs in almost every country contain the largest existing storage of fresh water. In the United States, ground water storage exceeds by many times the capacity of all surface reservoirs and lakes, including the Great Lakes (Johnson,1966). In addition to abundance and ubiquitous presence, ground water is not subject to evaporation as is surface water, and its temperature fluctuates only slightly from the mean annual temperature of the area. These are important considerations, especially in arid regions where potential evaporation exceeds precipitation or pumping rate. Ground water is basically pure, that is, unpolluted, depending of course, upon the type of aquifer, its depth, and proximity to potential sources of contaminants. A granular aquifer tends to filter the water migrating through it, thus removing suspended material and biological matter. Ground water is nearly always biologically more pure than surface water. Exceptions may occur where dense carbonate aquifers contain water in fractures and solution openings where the flow is similair to that through open pipes. Filtering cannot take place and contaminants entering the aquifer from above, as, for example, leakage from septic tanks may render the reservoir useless unless the water is chlorinated or otherwise treated.

Of course, not all the water stored in the ground is available for practical use because of problems regarding accessibility, dependability, quality and cost of development (Johnson, 1966).

The following pages of this report contain an aquifer analysis based on data from a pumping test in northwestern Ohio. The well is located in Williams County, Bridgewater Township, E ½, NE ¼ of section 25 (Fig 2). The production well and two observation wells were drilled by cable tool method. The production well is 37 feet deep, with a diameter of 10 inches, is cased to 27 feet, and is finished with 10 feet of # 10 slot screen. The original production well was drilled to a depth of 207 feet. However, an insignificant amount of water was encountered below 37 feet, thus the drilling contractor attempted to pull the casing back to expose the water-bearing formation encountered at 18-37 feet. The casing could not be pulled, so a second well was drilled near the original. The two 6 inch observation wells, which are 50 and 150 feet from the production well, are finished with 3 feet of screen, and are also 37 feet deep.

AREAL GEOLOGY

Geologically, the well is drilled in ground moraine. The area was covered by both Illinoian and probably 2 separate Wisconsin glaciers, and the till is about 205 feet thick. Ground moraine is a smooth surfaced till deposit, composed of an unsorted and unstratified mixture of clay, silt, sand, and coarser fragments deposited by the ice. Boulder sized debris was encountered in drilling the wells. Glacial till controls ground water availability in approximately 30% of the world, yet in spite of its importance as an aquifer, very few data on till permeability have been published. The reason for this dearth of information is probably the feeling that there is insufficient continuity of sand or gravel lenses in the till to make any application of quantitative values practical. There is evidence, however, that till deposits are actually

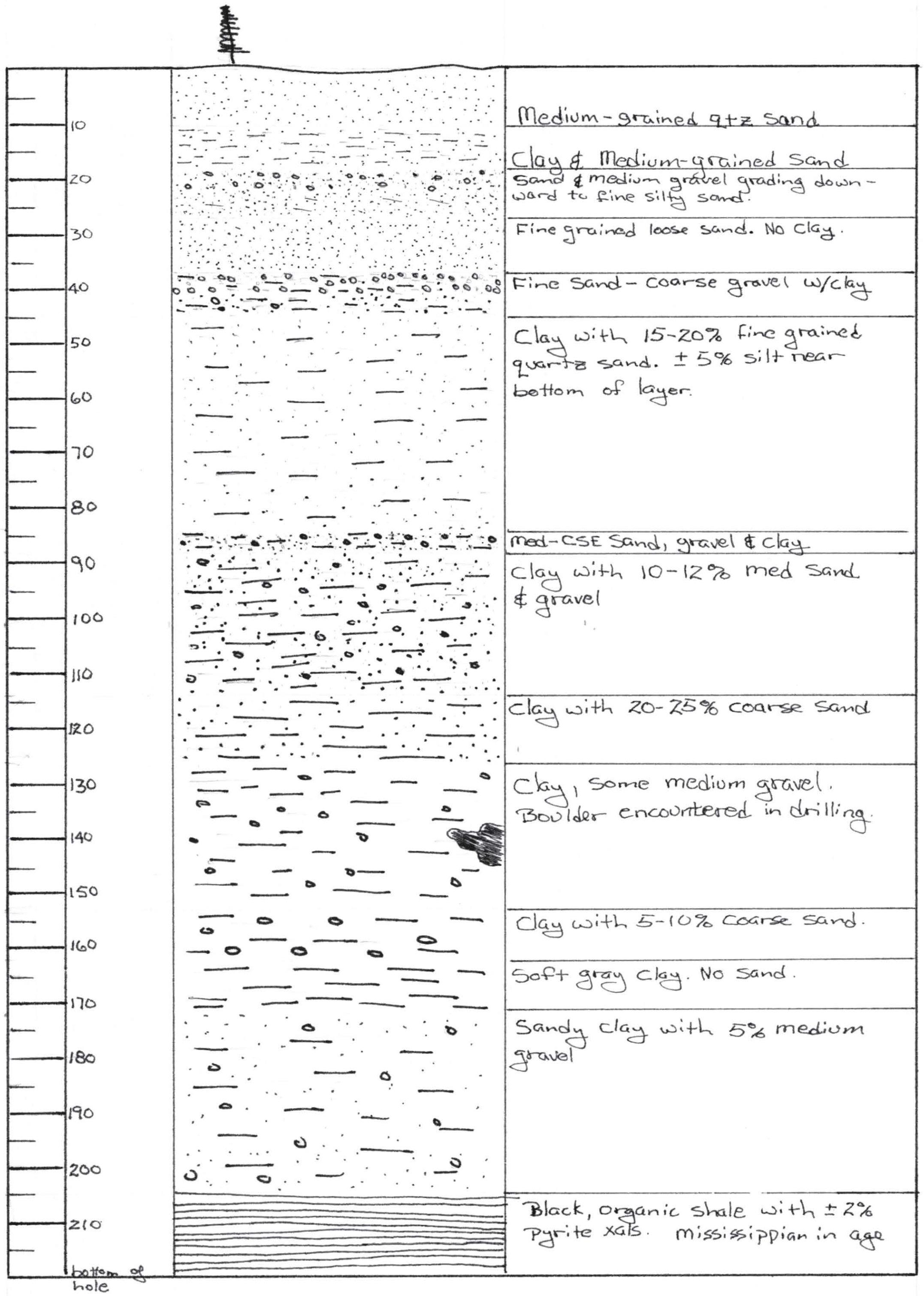


Figure 3. Lithologic log of local strata.

reasonably uniform in permeability (Norris, 1962).

Bedrock below the till is black shale of Mississippian age. The shale is finely laminated, highly organic, and contains 1-2% pyrite crystals. Water from bedrock is highly mineralized.

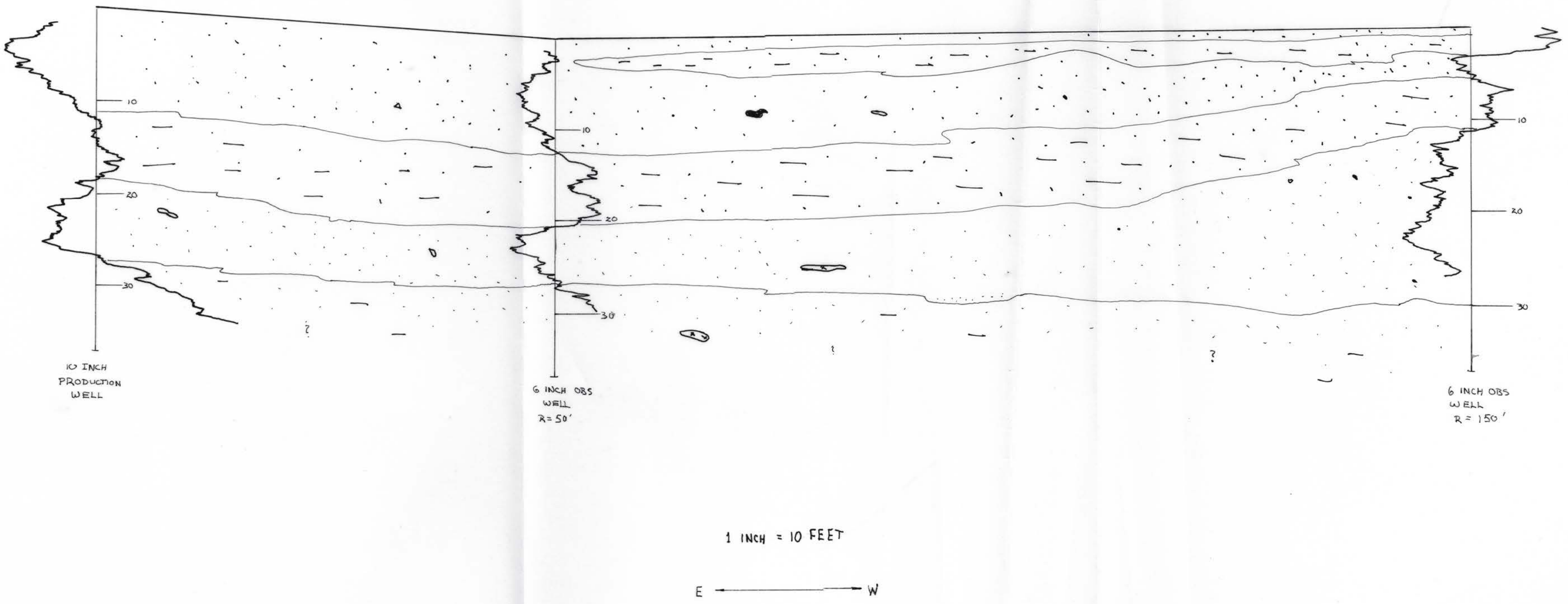
The aquifer under consideration consists of unconsolidated sand about 19 feet thick. The shape of the aquifer is somewhat lensoid. There is no indication that the aquifer is very extensive laterally. The aquifer is overlain by till. The aquifer is artesian and the static water level was 5.5 feet below land surface datum on July 27, 1969. There is vertical leakage downward through the sand-clay layer above the aquifer.

Since the original production well was drilled through the drift and into the bedrock, a complete log of the glacial material is available. Figure 3 is a lithologic log with a description of the strata penetrated. Unfortunately, no record was kept of the drill cuttings in either of the observation wells. Therefore a geologic cross section based on actual cuttings is impossible to construct. However, after com;letion of the aquifer test, gamma- ray logs were made of all three wells by the U. S. Geological Survey. By correlation of these three logs, and comparison of the cuttings from the production well with the gamma-ray logs, a generalized cross-section was made (Fig. 4). It must be remembered though, that radioactivity logs are best considered as auxilliary to actual samples. The main advantage to radio-active logs is that they can be taken through casing.

GENERALIZED CROSS-SECTION

BASED ON GAMMA-LOG INTERPRETATION

Figure 4



The theory of the gamma-ray curve is relatively simple. All rocks contain radioactive material, but the amount is highly variable. The radioactive substances are undergoing constant disintegration during which electromagnetic waves are emitted. The most penetrating of these rays are the gamma rays. As a general rule, since shale or clay contains more radioactive material than sandstone or limestone, shale produces a prominent reaction or "kick" in the gamma-ray curve. Clay or shale produces a "kick" to the right, clean sand reacts to the left, and there is a complete gradation between the two extremes. A gamma-ray log of the screened portion of a well is often difficult to interpret because of the uneven bombardment, since some rays come directly through the openings of the screen and others are somewhat deflected.

PROCEDURE

The aquifer test took place during the period July 28-31, 1969. A turbine pump with a 300 gpm (gallons per minute) capacity was set at a depth of 26 feet. Power was supplied by a gasoline engine with a direct drive transmission. To measure discharge, a circular orifice weir was used. Figure 5 shows detailed construction of the apparatus. The orifice is a perfectly round steel plate with a hole of known size in the center. It is bolted against the outer end of a level discharge pipe, which is at least 6 feet long. At a distance of 2 feet from the orifice, the discharge pipe is tapped and a piezometer tube is

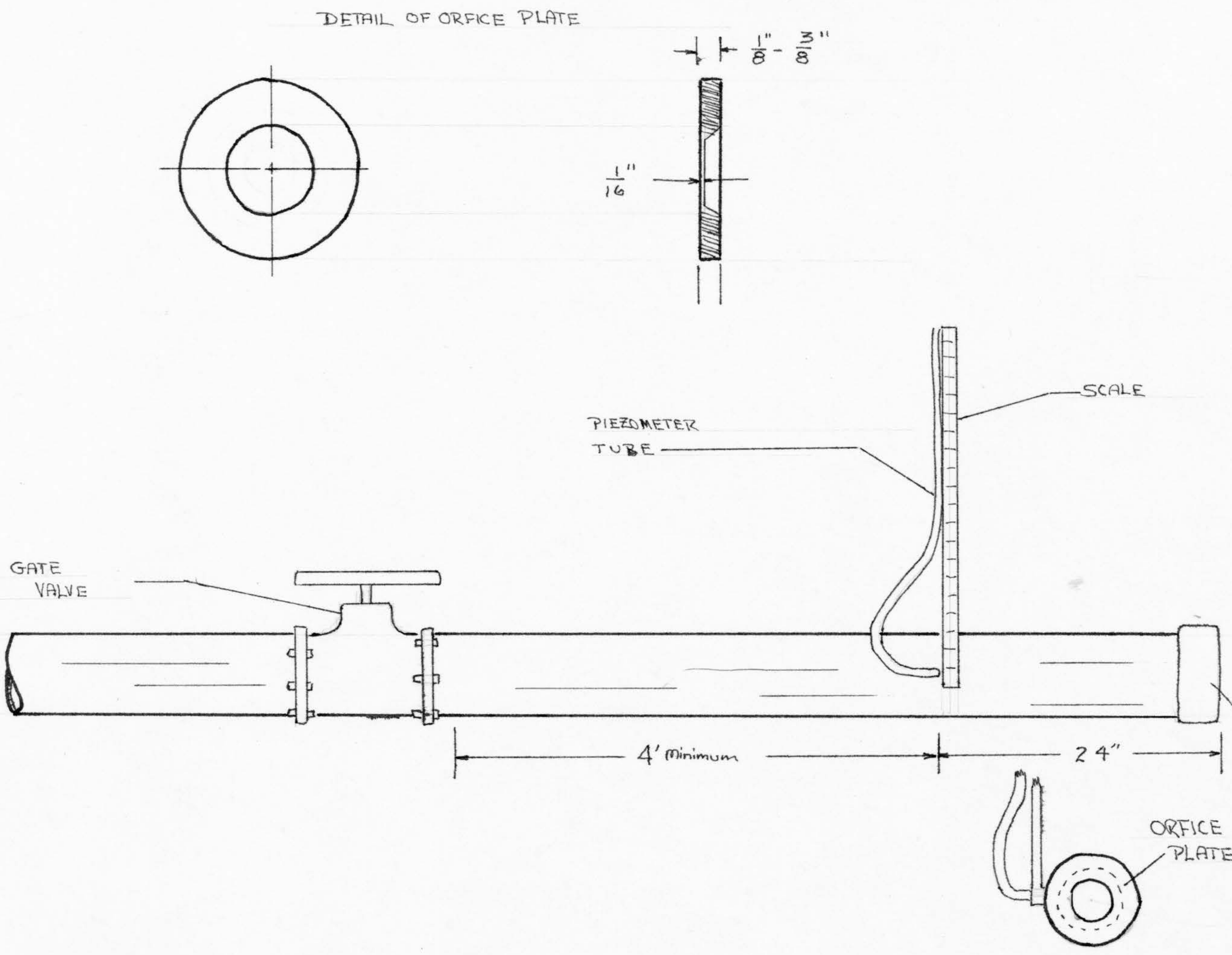


Figure 5. Detailed drawing of typical circular orifice weir.

inserted. The pressure head on the orifice can then be measured from the water level in the piezometer. For any given size of orifice discharge pipe, the rate of flow through the orifice varies with the pressure head. Standard tables for discharge with different pressure heads and orifices are published, or discharge can be calculated. Discharge is controlled by the speed of the power supply unit, or by a gate valve on the discharge pipe.

Before beginning the actual aquifer test, a trial aquifer test is run to insure proper functioning of the pump, engine, and the other equipment. This test should be of sufficient length to insure proper development of a new well, and to establish a discharge rate that can be maintained for the duration of the pumping test. Once Q (discharge, in gpm) has been chosen, the gate valve and the power take off unit should be set before the test is terminated. Once these preliminary adjustments are made, the pump should be shut down, and the system should be given sufficient time to recover before the actual aquifer test is begun.

Aquifer analysis by pump testing is one of the primary methods of determining hydraulic properties of aquifers and confining beds. The drawdown effect, caused by a well pumping at a constant rate, is measured in the pumping well and in various observation wells. Graphs of time vs drawdown and distance vs drawdown are used to solve formulas that numerically express the relation between the aquifer and the lowering of its water level. Decisions as to which formulas and graphs to use depend on the pressure conditions in the aquifer, the boundaries present, and the experience of the person doing the analysis.

The tested aquifer is artesian, and has a static water level 5.5 feet below land surface. The top of the aquifer was penetrated at a depth of about 18 feet, and the base was penetrated at a depth of 38 feet. Overlying the artesian aquifer is a confining bed of till that is 7 to 10 feet thick. Above the confining bed is a layer of sand that averages about 10 feet thick. The unconfined water table in the shallow aquifer is 2 to 3 feet below land surface.

Several different methods were used to find values of storage and transmissibility. The reason was to obtain as many values as possible to see if there is any similairity between the results of different methods.

The non-leaky artesian formula developed by C. V. Theis in 1935 was first used. The Theis formula states (Walton, 1962);

$$s=(114.6Q/T)W(u)$$

where:

s=drawdown in feet

Q=discharge, in gpm

T=transmissibility in gallons per day per foot

and

$$W(u)=\int_u^\infty e^{-u}/u\,du = -0.5772 - \ln u+u - (u^2/2.2!) + (u^3/3.3!) - (u^4/4.4!)\ldots$$

where:

$$u=1.87r^2S/Tt$$

r=distance, in feet from center of pumped well to point where drawdown is measured

S=coefficient of storage, dimensionless

t=time since pumping started, in days

The exponential integral written symbollically as W(u) is called the "well function of u." The nature of the integral, and the presence of two unknowns makes an exact analytical solution impossible. However, values of u and W(u), obtained from special tables (Walton, 1962), can be plotted on log-log graph paper to produce a type curve from which values can be obtained for application of the formula

In this report, two variations of the Theis method were used. The first method plots r^2/t vs drawdowns, and the second plots time (t) vs drawsowns. These values are plotted on log-log paper of the same scale as the type curve. One then attempts to match the type curve with the data plot, keeping the axes of the graph paper parellel. When a best fit is obtained, a convenient match point is chosen, and the coordinates of this match point are substituted in the proper equations for values of T and S.

The Theis formula was developed on the basis of six assumptions: that the aquifer is infinite in extent, that it is homogeneous, that its transmissibility is constant at all places in all directions, that it is confined between impermeable beds, the coefficient of storage is constant, and that water is released from storage instantaneously with a decline in artesian head (Heath and Trainer, 1968).

These six conditions are seldom if ever met in nature, so one must adjust the results of the Theis equation to explain existing conditions. If the drawdown in observation wells falls below the type curve, this implies that some sort of recharge boundary was reached by the cone of depression, or that vertical leakage was occurring, or both.

The leaky artesian formula, developed by Hantush and Jacob (1955) is used to evaluate an artesian aquifer that is being recharged by vertical leakage from one of its confining beds. It is a method used when a confining bed is not impermeable. The leaky artesian formula may be written as:

$$s = (114.6Q/T)W(u,r/B)$$

where:

$$u = 2693r^2S/Tt,$$

$$r/B = r\sqrt{T/(P'/M')}$$

and the other terms are as previously defined. $W(u,r/B)$ is read as the "well function for leaky artesian aquifers," and is defined as:

$$\int_u^{\infty}(1/u)\exp(-u-r^2/4B^2u)\,du$$

Values for u and $W(u,r/B)$, which can be obtained from special tables, are plotted on log-log paper to construct a family of leaky artesian curves (Walton, 1962). This set of curves can be matched with time-drawdown data to obtain values for transmissibility, storage, and vertical permeability of the confining bed. The leaky artesian formula is based on these following assumptions: the aquifer is of infinite areal extent, and is the same thickness throughout, that it is homogeneous, and isotropic, that it is confined between an impermeable bed and a bed through which leakage can occur, that the coefficient of storage is constant, that water is released from storage instantaneously with a decline in head, that the well is infinitesimal in diameter and penetrates the entire aquifer, leakage through the confining beds is vertical and proportional to drawdown, that hydraulic head in the deposits supplying leakage remains more or less uniform, that flow is vertical in the confining bed and horizontal in the aquifer, and, that storage in the confining bed is neglected (Walton, 1962).

In an attempt to determine if recharge to the aquifer is a result of a recharge boundary such as a stream or whether it is due to vertical leakage, a distance drawdown plot on log-log paper was made, near the end of the 24 hour period, when conditions of drawdown were nearly steady. Distance-drawdown data were matched with the steady state leaky artesian type curve trace. If a recharge boundary is crossed, the distance-drawdown curve, which is a profile of the cone of depression, will be distorted, and the time-drawdown and distance-drawdown values for transmissibility will be different. The average value of T for time-drawdown and distance-drawdown is 28,100 gpd/ft and 87,500 gpd/ft respectively. These values are strikingly different, which is a possible indication of a recharge boundary.

There are, however, several sources of error in this comparison. First, there are only 2 observation wells, hence only three points on the distance-drawdown curve, including drawdown in the pumped well. Second, according to the gamma-ray logs, the aquifer is thickening to the west (Fig. 4). As a result of this thickening, the 150 foot observation well, and the 50 foot observation well have a greater exposure of the aquifer, which would result in less drawdown, and a greater T. There is also a probability that leakage occurs from above and below the aquifer.

In an attempt to gain possible further information about the aquifer, the modified non-leaky artesian formula of Jacob was applied to both time-drawdown, and distance-drawdown data. The Jacob method is ordinarily used on artesian aquifers under steady shape or steady state conditions, or when u is very small. It has been specifically noted that the Jacob method should not be used when hydraulic boudaries develop before steady state conditions are reached, or when leakage from confining beds occurs (Heath and Trainer, 1968). However, values of transmissibility and storage could be of value when compared to the same coefficients derived from other methods. Specifically, in this case, values of T from the Jacob method are considerably larger than values previously calculated. Large values of transmissibility might also imply that the test is affected by partial penetration. Values of transmissibility will be low if the pumping well and the observation wells are screened in the same zone of the aquifer, and high if they are screened in different zones.

Values of transmissibility computed by the various methods ranged from as high as 87,500 gpd/ft, to as low as 23,500 gpd/ft. An average value of T is very close to 50,000 gpd/ft. Values for storage showed an even greater variance, with coefficients ranging from water table to highly artesian conditions. The average coefficient of storage was .112, but this value is weighted by a single value of .989. Instead of the average, a median value of .002860 will be used as a representative coefficient of storage. Vertical permeability of the confining bed was calculated to be .127 gpd/ft^2. Permeability of the aquifer, using an average aquifer thickness of 17 feet is 2940 gpd/ft^2.

The future of an aquifer depends on how well the water budget is managed. If the pumping rate exceeds the recharge rate, the aquifer is dewatered, and will eventually cease to be productive. To plan a water budget then, it is first necessary to know how much water is available for recharge. Norris (1959) has pointed out that in Ohio, the average period of time for water table recharge is five months. The remaining seven months are a period of depletion, during which time, evapotranspiration and runoff exceed infiltration. To avoid mining an aquifer then, it would be necessary to pump at such a rate that the water removed during the seven month depletion is less than or equal to the amount of recharge that can reasonably be expected during the balance of the year.

Now that we have some idea of the hydraulic properties of the strata, and some idea of the relationship of the beds, let us recall our original definition of an aquifer. An aquifer is a layer or layers of rock, sufficiently permeable to supply a substantial quantity of water to a well. Using the information afforded by aquifer test data, and by making several necessary assumptions, it is possible to say, within limits, how much water is available from the ground storage in the vicinity of this particular well. It must be kept in mind that the entire evaluation is highly theoretical, and while the figures are probably "in the right ball park", they could be misleading as well.

For purposes of illustration, let us pick an effective radius of 3000 feet for the well. This results in a cone of depression with a top surface area of one square mile. If the production well were to pump continuously over the 7 month depletion period at a rate of 80 gpm, the total amount of water taken out of storage is 2.3×10^7 gallons. A well pumping at a rate of 33 gpm for a period of 1 year will cover with water a one square mile area to a depth of one inch. In other words, 1 inch of rain over a square mile area is equal to 33 gpm/year. In a period of 210 days, this is equal to 10×10^6 gallons. Three inches of rainfall over a square mile area would be enough to replace the water removed through pumping over a 7 month period, assuming that all of the rainfall reaches the aquifer. Also, one could reasonably expect more than three inches of rain in a 7 month period in Ohio. As shown in the cross section (Fig. 4), the aquifer is overlain by a confining layer with a vertical permeability of .127 gpd/ft^2. Assuming the confining bed to be reasonably uniform, and a head difference of 4 feet throughout, then $Q = P'/m'Ah = .0725$ gpd/ft^2, or a vertical leakage factor of 2 million gpd/mi.^{2}. There is then, sufficient recharge available through rainfall. Besides rainfall, there is the possibility of recharge through streams. While this may not take place directly into the aquifer, recharge of the surface layer of sand from the stream is highly possible.

Projecting the time-drawdown curve for the production well to a time of 210 days shows a drawdown of 19.8 feet, (Fig.11) assuming a uniform aquifer. Since there is an allowable drawdown of 26 feet in the production well, it is reasonable to expect at least 80 gpm, and probably as many as 100 gpm for periods of sustained pumping. We know that 2Q = 2(drawdown), therefore, a pumping rate of 100 gpm = 1.25Q =1.25(drawdown). Multiplying the projected drawdown by a factor of 1.25 shows that the drawdown at the end of 210 days pumping at 100 gpm will be 24.8 feet.

One final consideration to be made, is the chemical quality of the water. A producing well is useless if the water pumped requires extensive treatment before it can be used. A water sample was collected from the discharge pipe after pumping for 24 hours. Complete chemical analyses were made by the USGS laboratory. A brief discussion follows:

Iron content was found to be 2 ppm, which is high enough to cause staining, and will probably support iron bacteria growth. Dissolved solids, at 360 ppm is well within the limit set by the Public Health Service (1962) of 500 ppm. Hardness as calcium carbonate was 298, which is quite hard, but not unusual in Ohio. Sulfate and chloride, at 17 ppm and 11 ppm respectively, show quite safe levels. The fluoride content was 0.8 ppm, which is a safe level, and highly desirable from a dental standpoint. Nitrate, a compound that indicates pollution from sewage wastes, plant debris, or fertilizer, is absent. The pH of the water was 7.7, which is normal for ground water. All indications are that the water from this well is safe for drinking. It should be tested further for various bacteria which can be detrimental to humans before being considered safe for consumption. The well should be treated at regular intervals for iron bacteria.

CONCLUSION

Well M-43 was drilled and tested by the State of Ohio. Upon completion of the aquifer analysis, rights to the well were turned over to the property owner. The well has a long-term capacity of at least 80 gpm, possibly as high as 100 gpm. Quality of the water is acceptable to the extent of present knowledge. The aquifer is artesian, with vertical leakage evident. Data gathered from M-43 will be compiled along with data from similair tests throughout the state in an effort to provide answers to questions of ground water availability both now and in the future.

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